Relativistic Electron-positron Plasma Jets Using High-intensity Lasers

Presentation to

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Collaborators

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Laser generated relativistic positrons have exciting properties

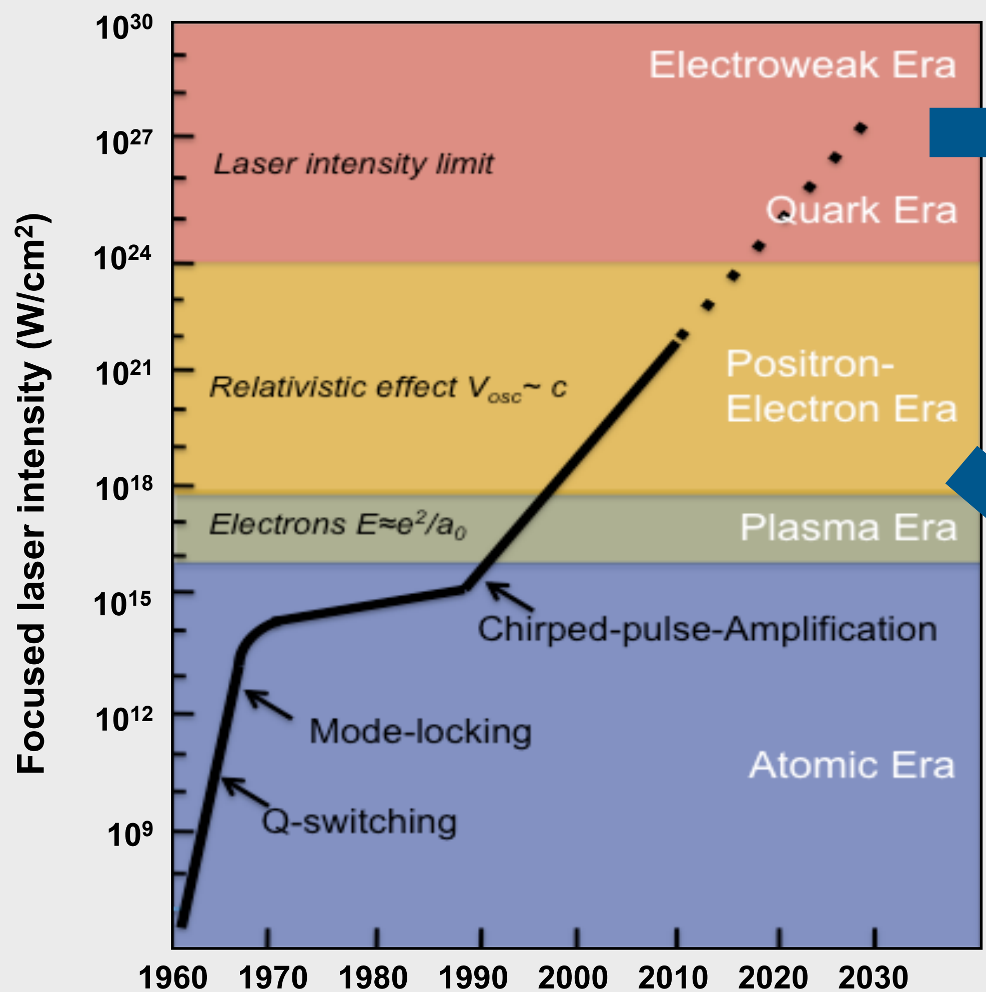
- **Fundamental pair plasma science at the relativistic regime**
- **Positron tomography for diagnosing high-energy-density plasma dynamics**
- **Pico-second gamma ray source at 511 keV**
- **New source for accelerators and positron science & applications**
- **Relativistic pair plasma jets for lab astrophysical studies**

2008 Chandra image of the nearby galaxy Centaurus A shows the effects of an active supermassive black hole as opposing jets of high-energy particles extending to the outer reaches of the galaxy.

Credit: NASA/CXC/CfA/R.Kraft et al

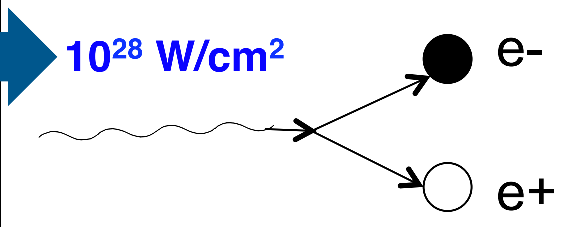
Why possible: advances in laser technology enable intense lasers to produce electron-positron pairs

Laser power evolution and accessible physics



Vacuum pair creation

Breit, Wheeler, Bunkin et al.



$$n\omega \rightarrow e^- + e^+$$

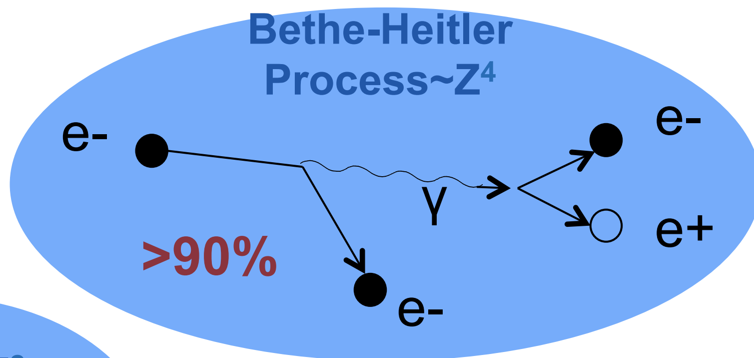
Typical parameters ~10^{20} W/cm^2

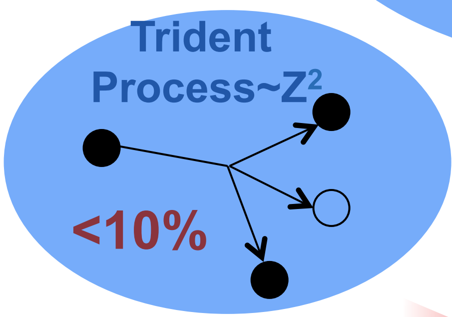
Electric fields	10^{12} V/m
Magnetic fields	100's MG

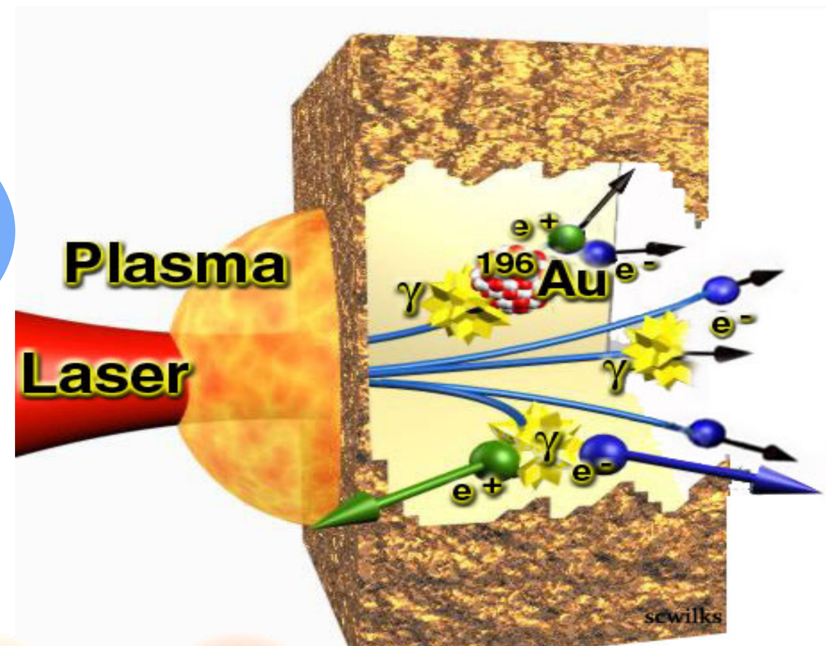
F = E + v×B

$$kT_{hot} = \left[\sqrt{\left(1 + \frac{I\lambda^2}{2.8\times 10^{18}}\right)} - 1\right] \times 511 keV$$

Lasers create positrons via two processes using targets with high atomic numbers

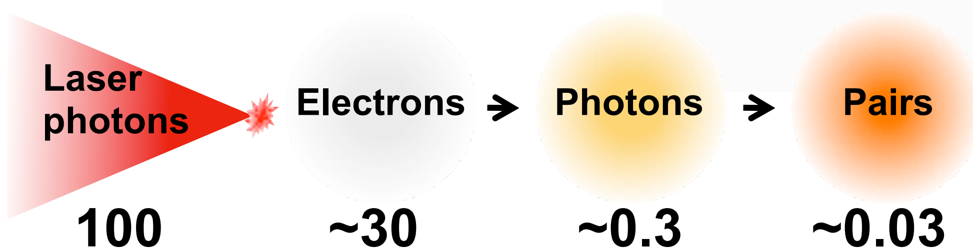






Wilks

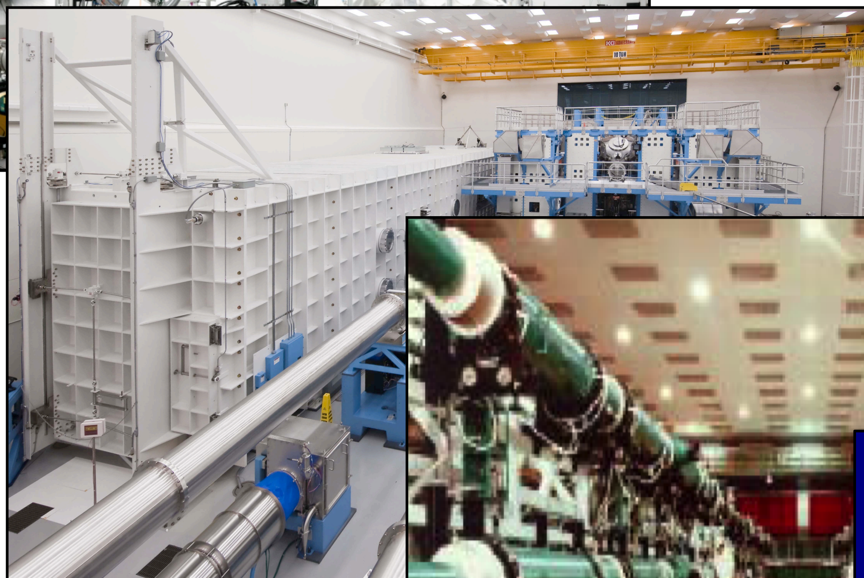
Energy Flow



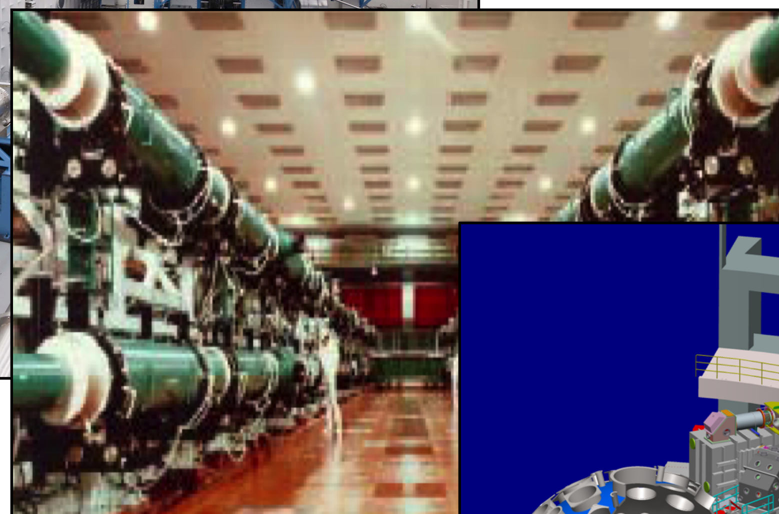
Maximizing the energy into >MeV electrons is the key to increase the efficiency of positron production using lasers

We have used and will use a number of large laser facilities to do the relativistic pair-plasma research

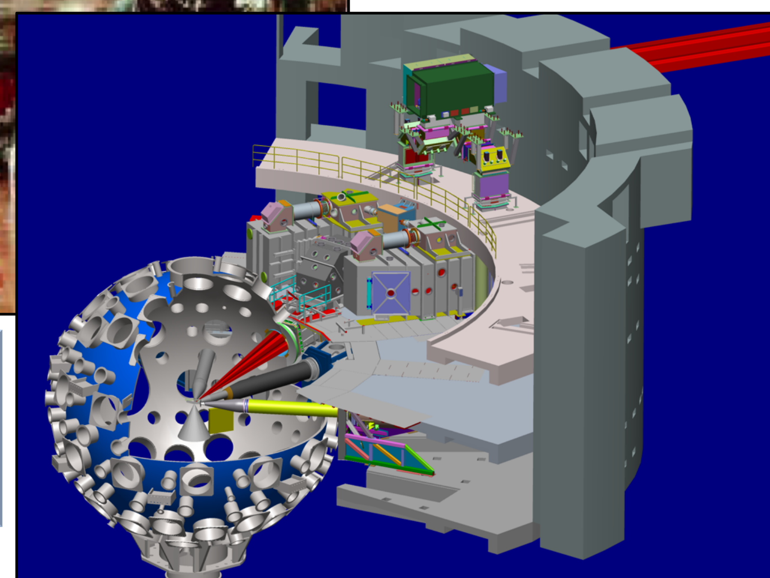
Titan laser (LLNL)
1-10 ps, 100-350 J
5-10 shots/day



Omega EP (LLE)
1-10 ps, up to 1.3 kJ
5 shots/day



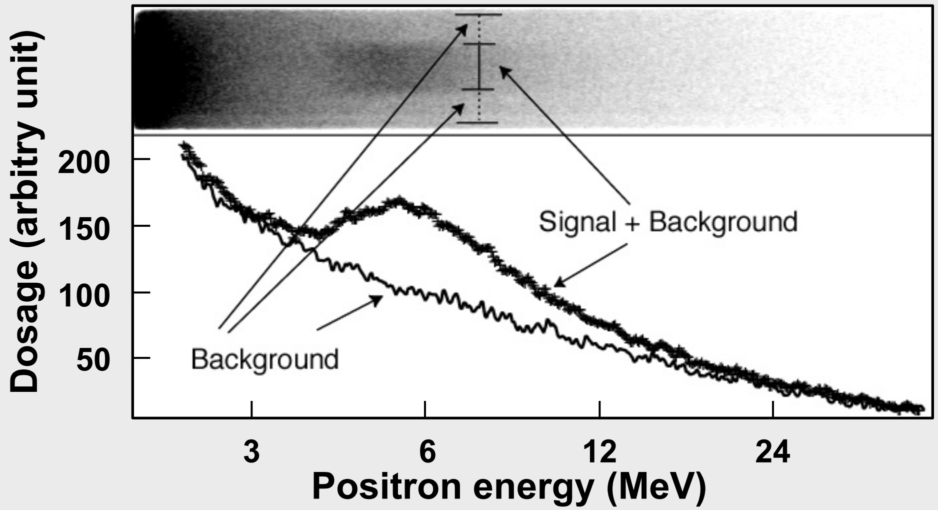
Gekko (ILE)
4 beams, 1 ps, ~1 kJ
Shots in 2012



NIF ARC (LLNL)
1-10 ps, up to 10 kJ
Shots in FY13 & 14

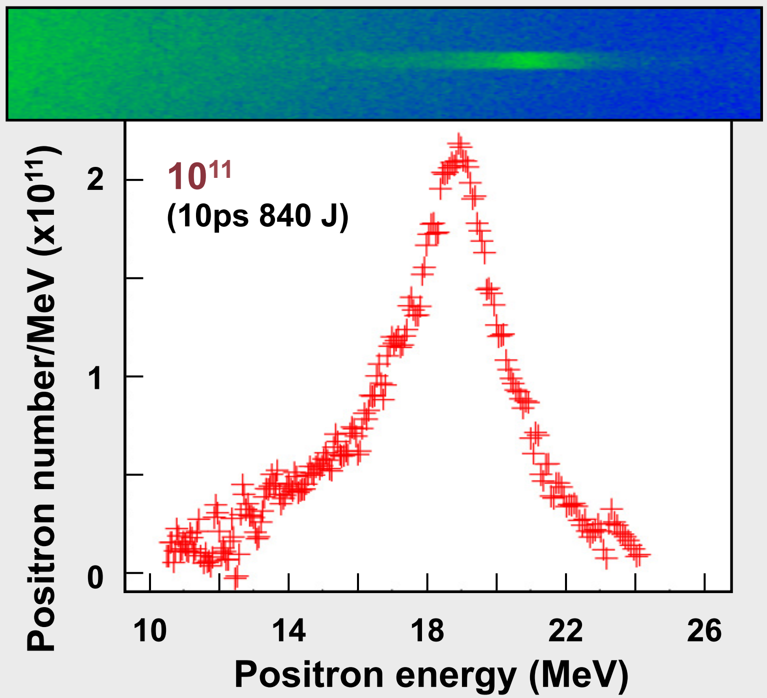
Our results show that intense lasers produce very high flux, relativistic pairs in very short time

Titan positron data image (Au, 1mm)



In this shot, about 10^6 positrons were observed in the detector, and about 10^{10} in 1 ps 120 J shot

Omega EP positron data #5082

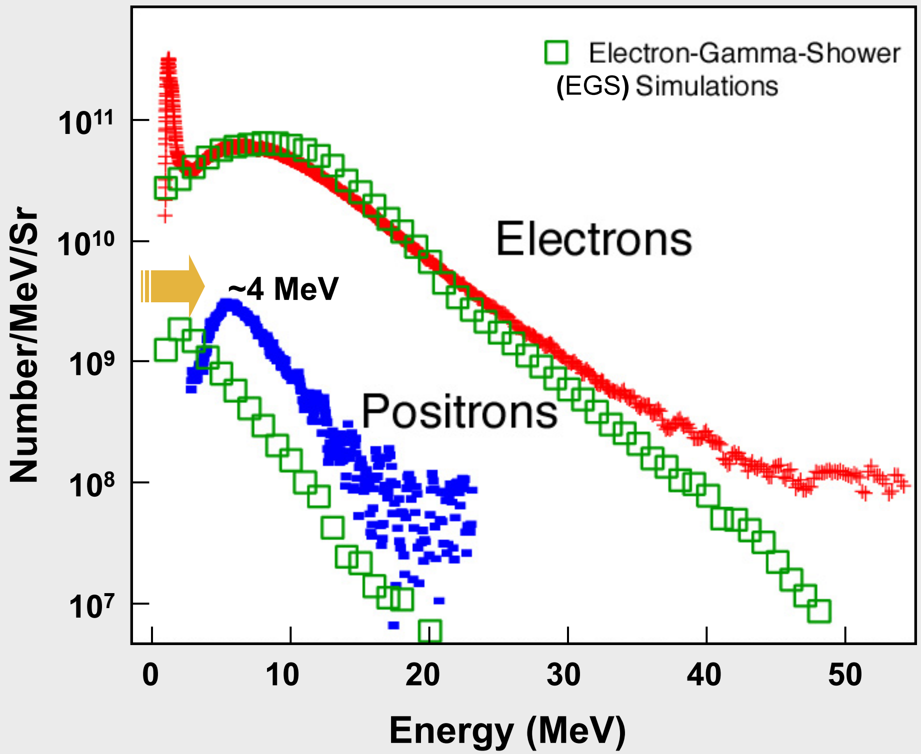


Chen *et al.*, PRL 2009

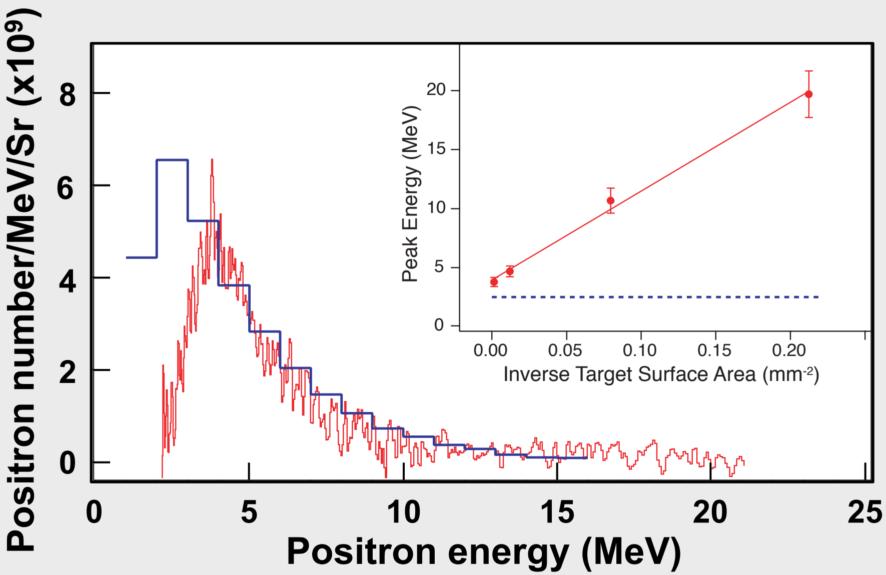
Pair number:	10^{10} - 10^{12}	Peak energy:	4 - 20 MeV
Pair flux duration:	~10 - 100 ps	E conversion:	>2x10^{-4}
Pair rate:	~10^{22} /s	Peak flux:	>10^{25} cm^{-2}s^{-1}

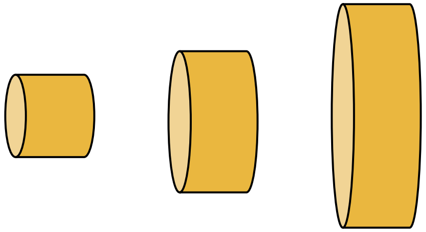
Positrons are accelerated by the target sheath electric fields 10s MeV

Electron and positron spectra



Positron accel. vs. target sizes

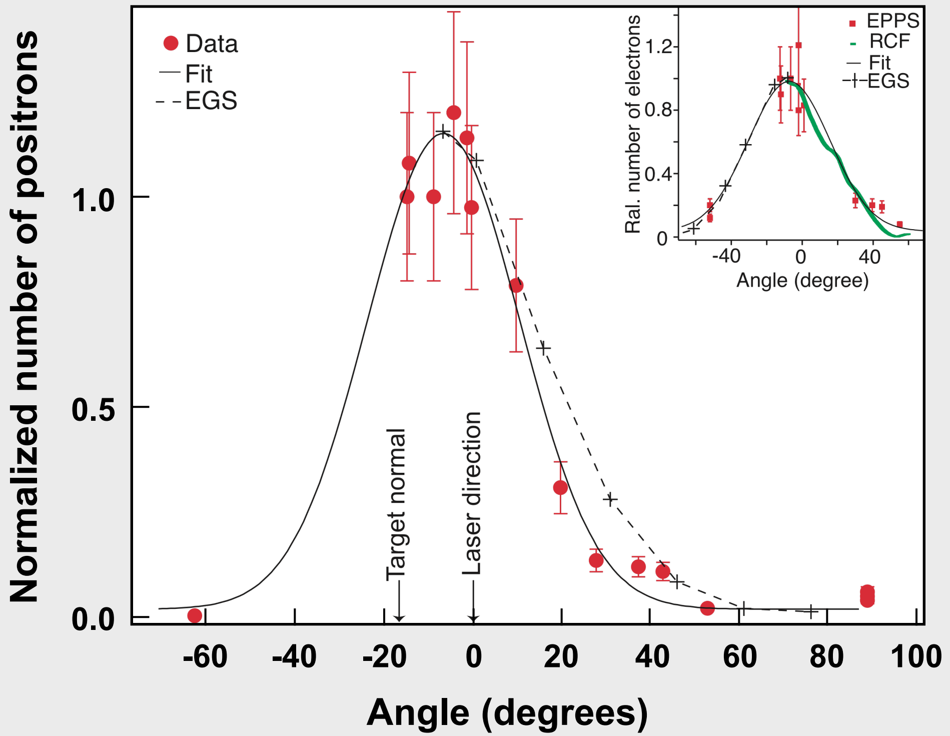




Positrons are accelerated at the same time by E-field, which shift the whole spectrum up in energy

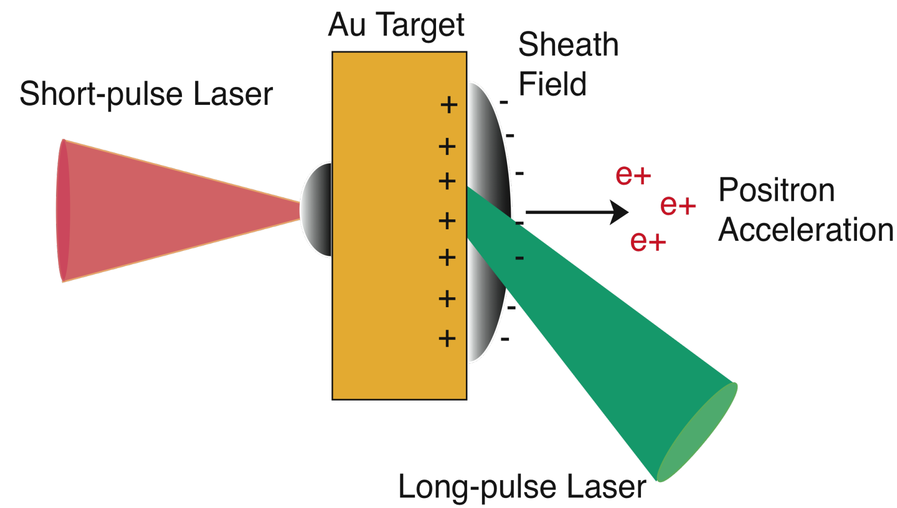
Laser produced relativistic pairs form jets at the back of the target

Laser pair angular distribution



Chen *et al.*, PRL 2010

Illustration of experimental setup

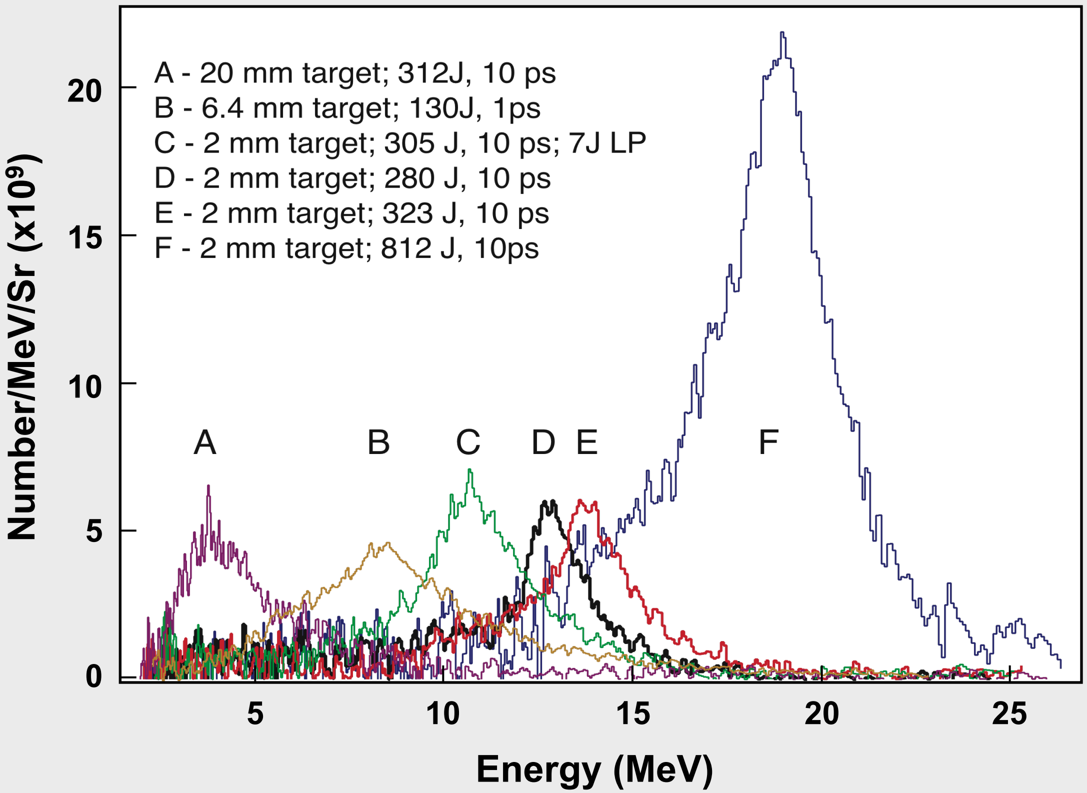


Jet angular spread: ~10-20 degree

The jets are shaped by the E and B fields of the target. Its direction is controlled by the lasers and target.

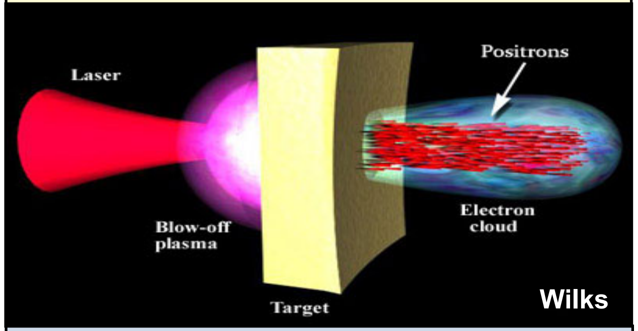
Laser produced positrons have a relativistic, quasi mono-energetic distribution due to sheath acceleration

Quasi mono-energetic positrons



Chen *et al.*, PRL 2010

Parameters of the pair



$T_{//}$: ~ 3 MeV;

$T_{\perp}$: ~ 1 MeV

dE/E: 50% - 20%

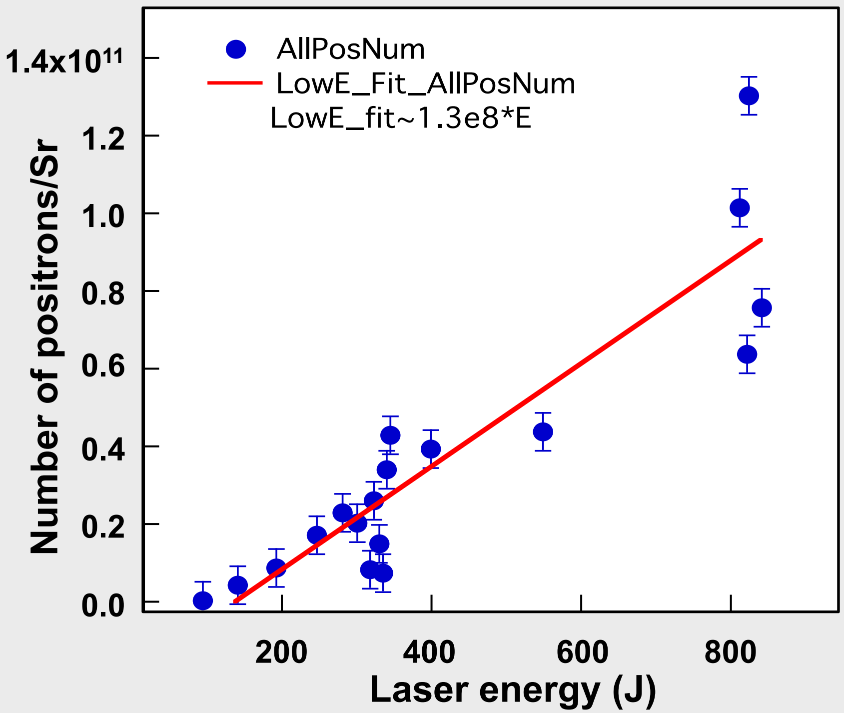
n_{e-}: ~10^{15} cm^{-3}

n_{e+}: ~10^{13} cm^{-3}

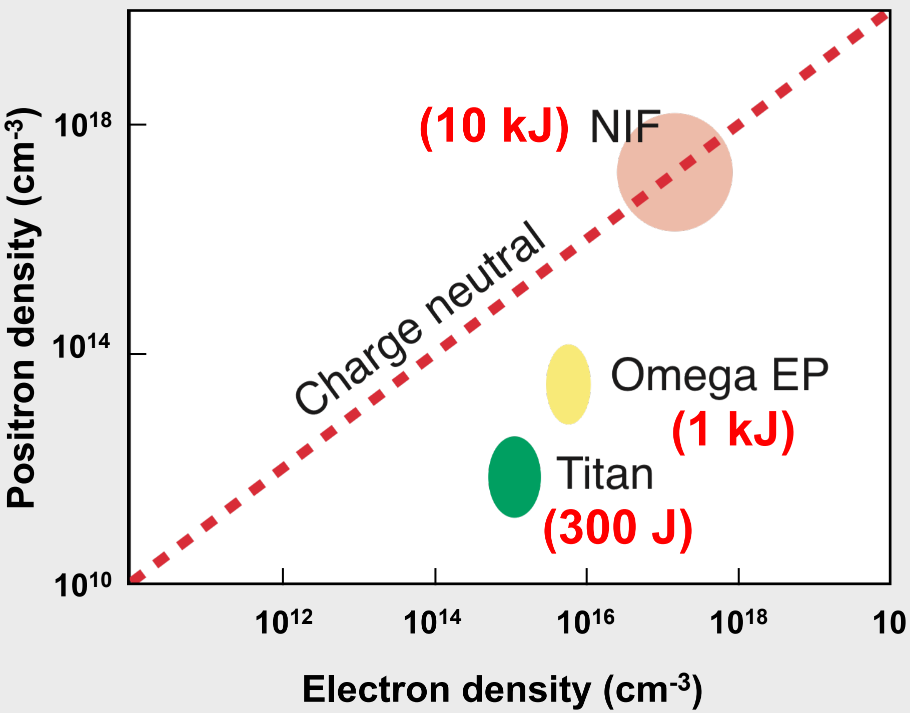
Non-neutral, high density, relativistic pair plasma jets have been made using lasers

Laser produced electron-positron pairs scale up with drive-laser energy

Positron number vs. laser E



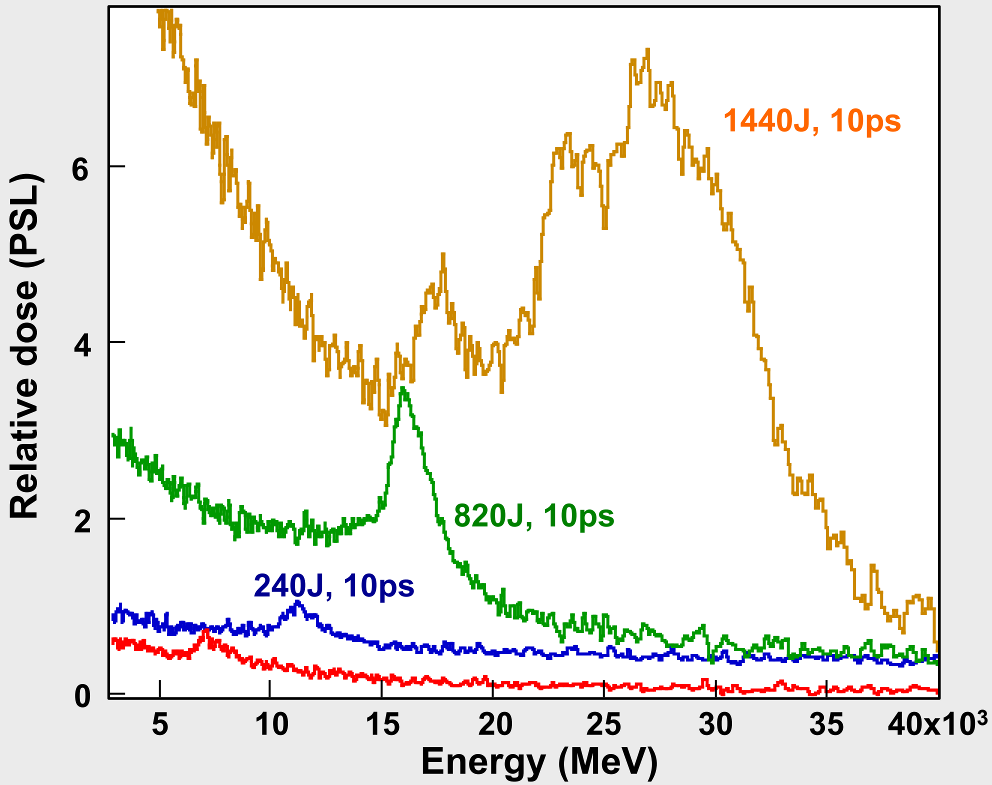
Positron jet vs. electron jet density



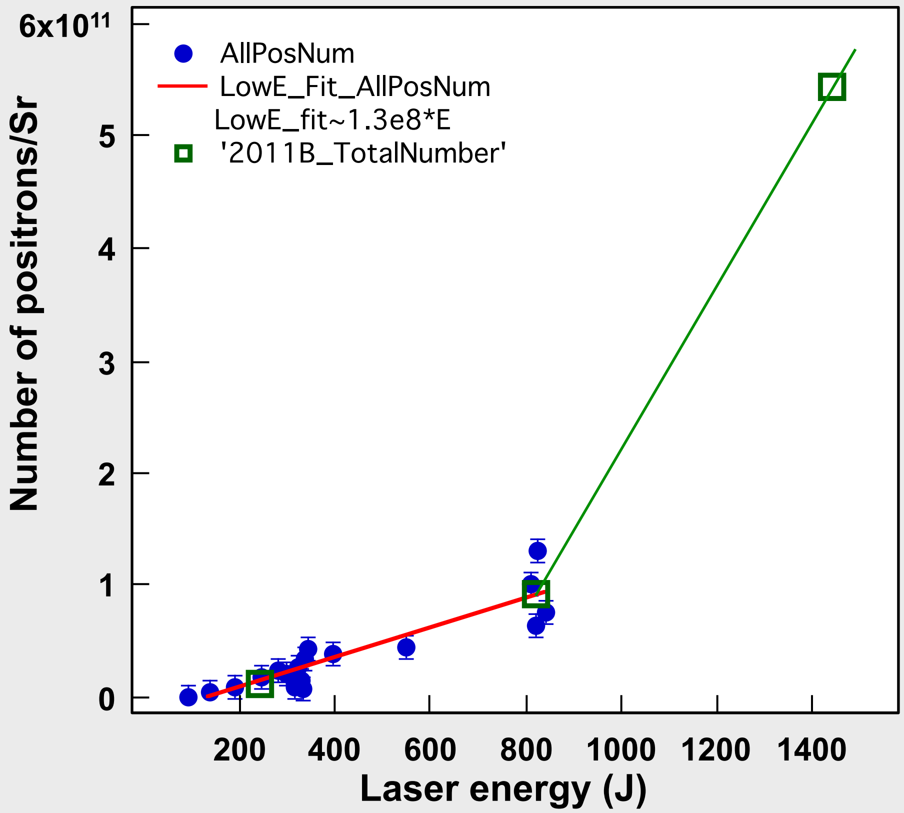
This feature is critical to future laboratory experiments using relativistic pair plasmas

Encouraging new trend appears when the laser energy exceeded 1 kJ (Omega EP experiments on Sep. 7)

Raw positron spectra from Omega EP

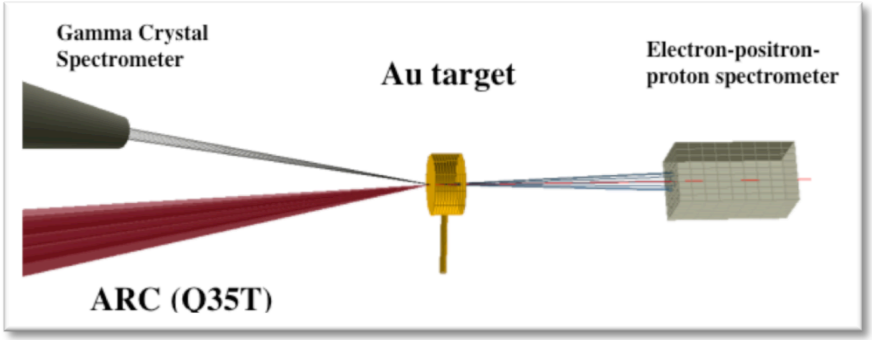


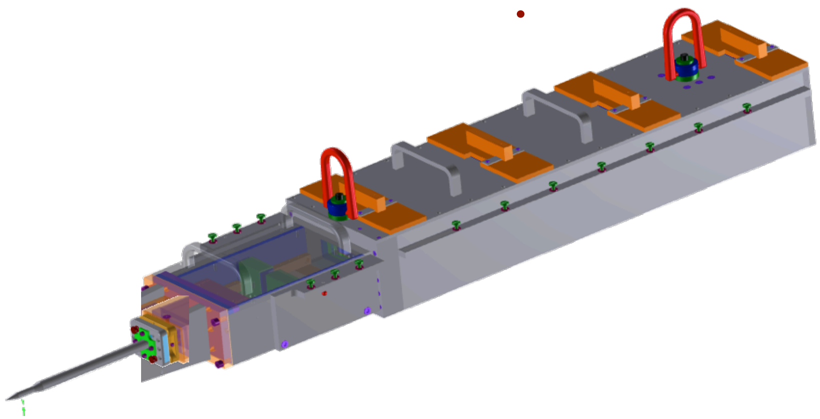
Preliminary: positrons vs. energy

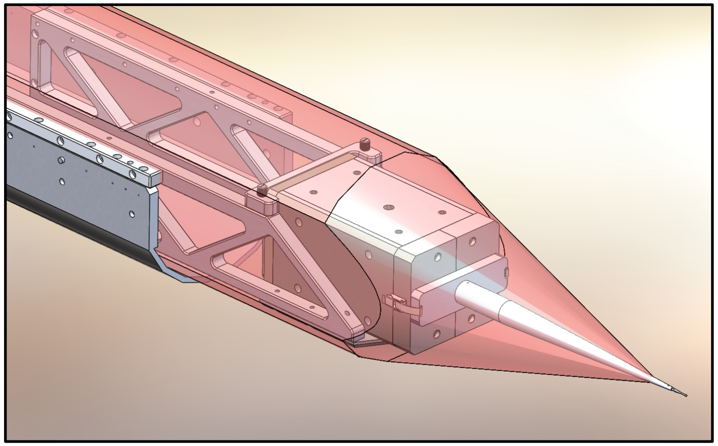


Is this an indication of non-linear scaling of positron generation at E > kJ?

EPPS and GCS have been designed, qualified and tested on OMEGA EP (TIM)



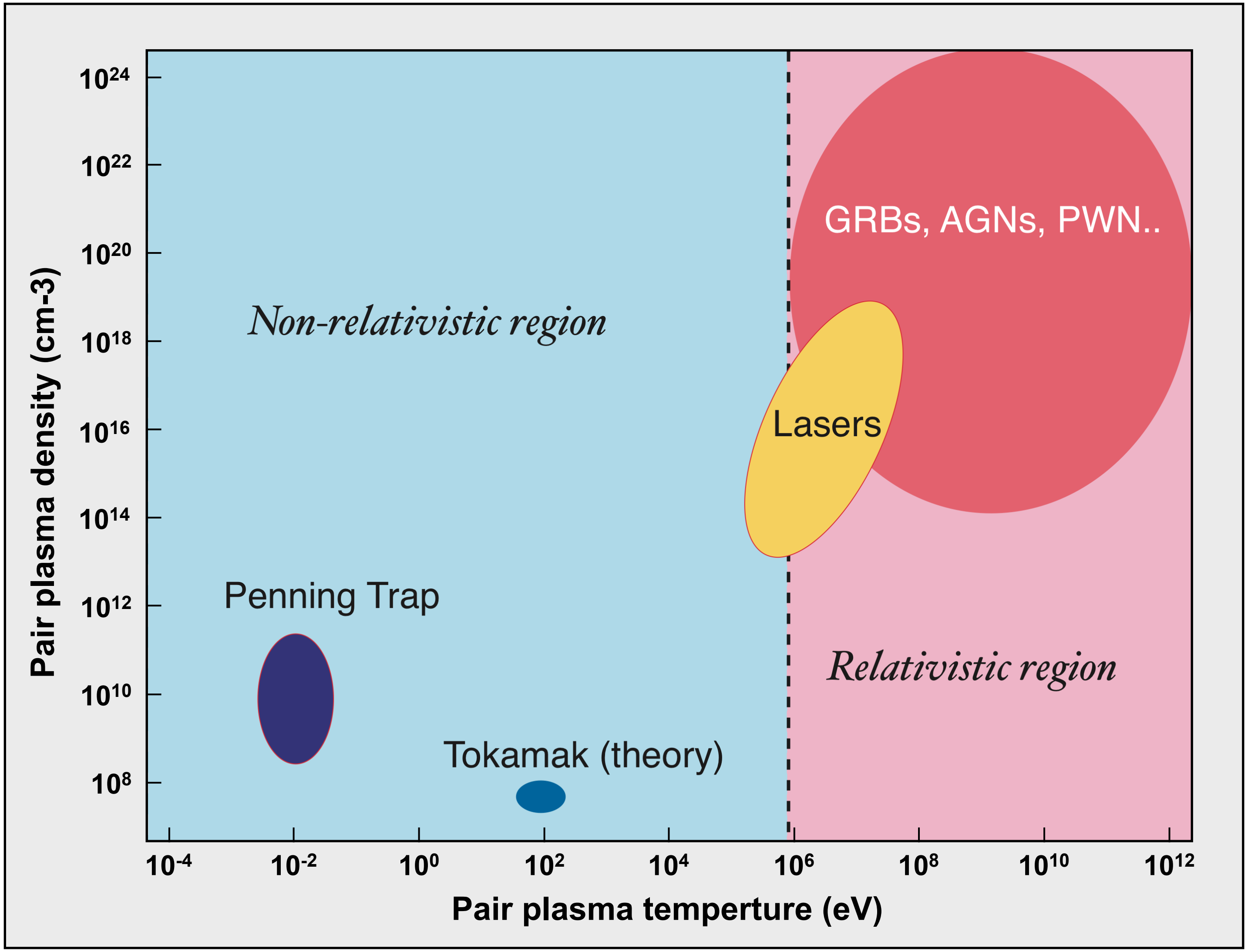




- EPPS provides absolutely calibrated electron/positron/proton spectrum for a large energy range (0.01 MeV – 400 MeV)
- GCS has energy coverage between 20 keV – 700 keV

The existing design can be improved for use on a NIF DIM

Soon we will access the conditions of some of the most energetic events in the universe in the lab



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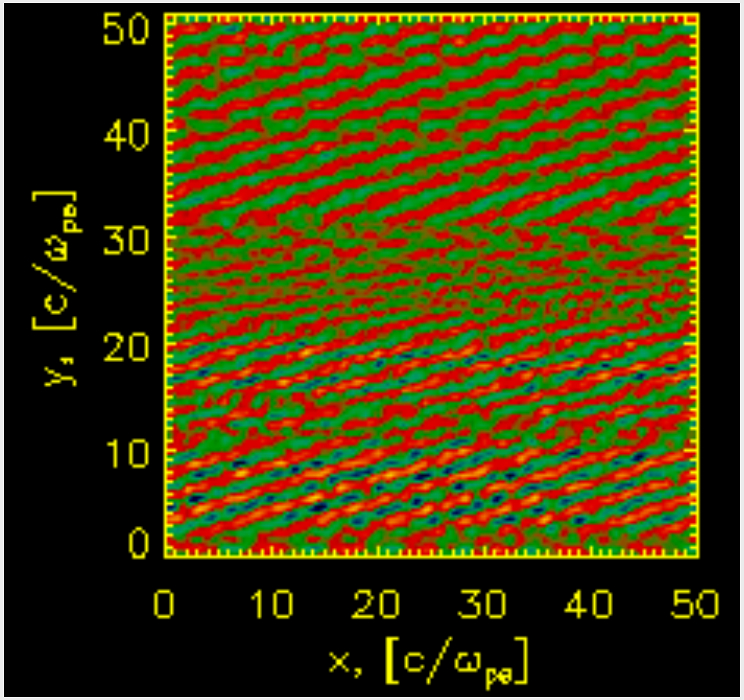
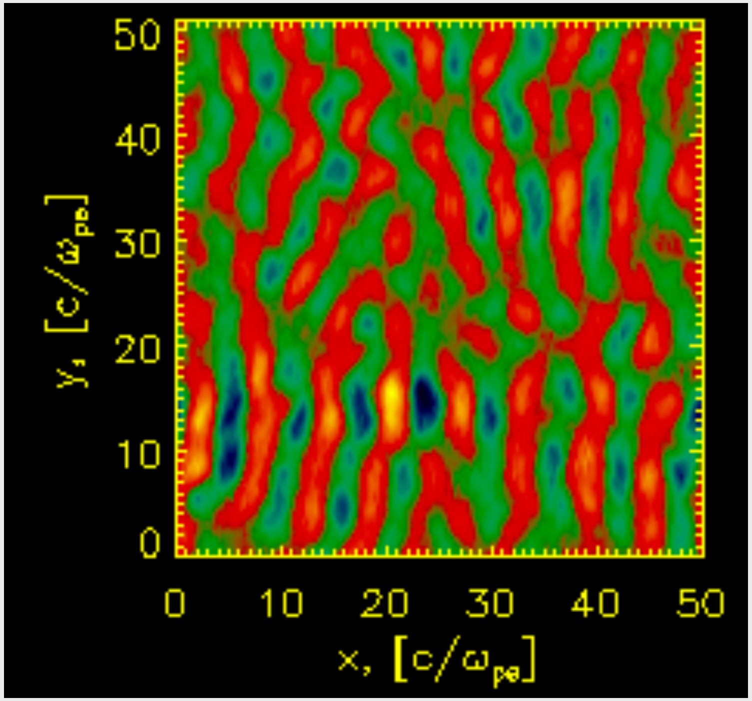
Rel. Pair beam — **Normal plasma**

Exponential growth (oblique mode)



Saturation (two-stream mode)

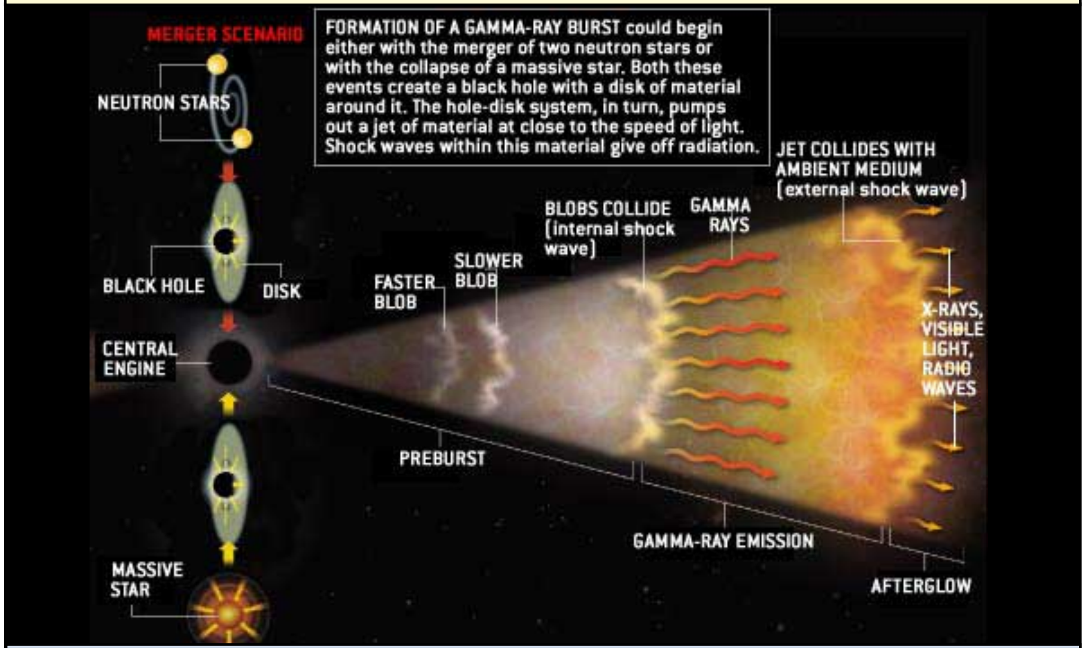


Anatoly Spitkovsky *(Princeton University)*

Induced EM instabilities may generate magnetic fields in intergalactic space around Active Galactic Nuclei

We will use laboratory pair jet interaction to understand astrophysical phenomena

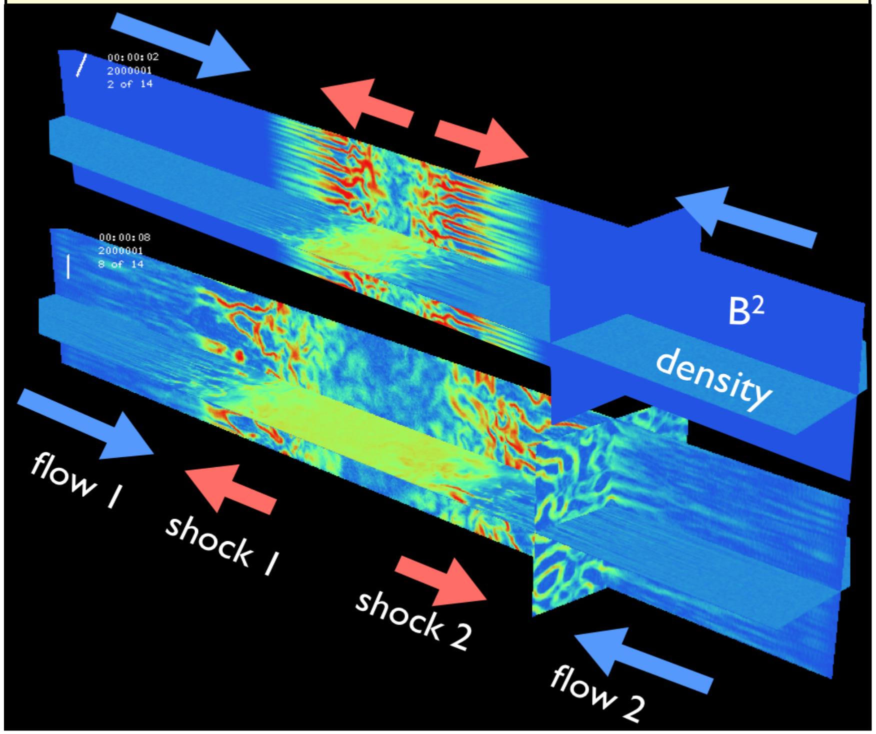
Gamma-ray-burst (GRB) physics model



Internal shocks give off radiation/particles

CNEA

Jet collision creates shock



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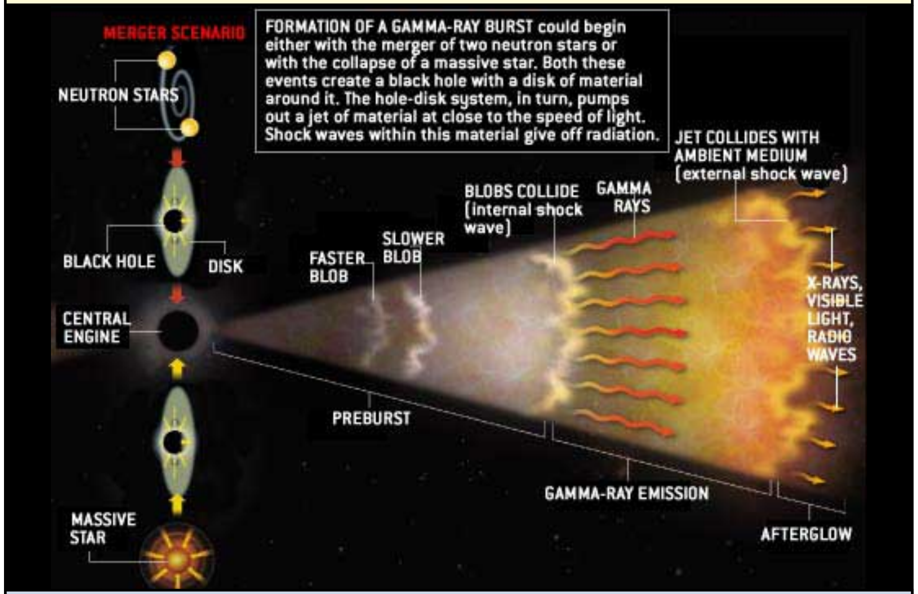
Colliding jets can mimic the internal shock of GRBs, allowing study of how energy is transferred to particles

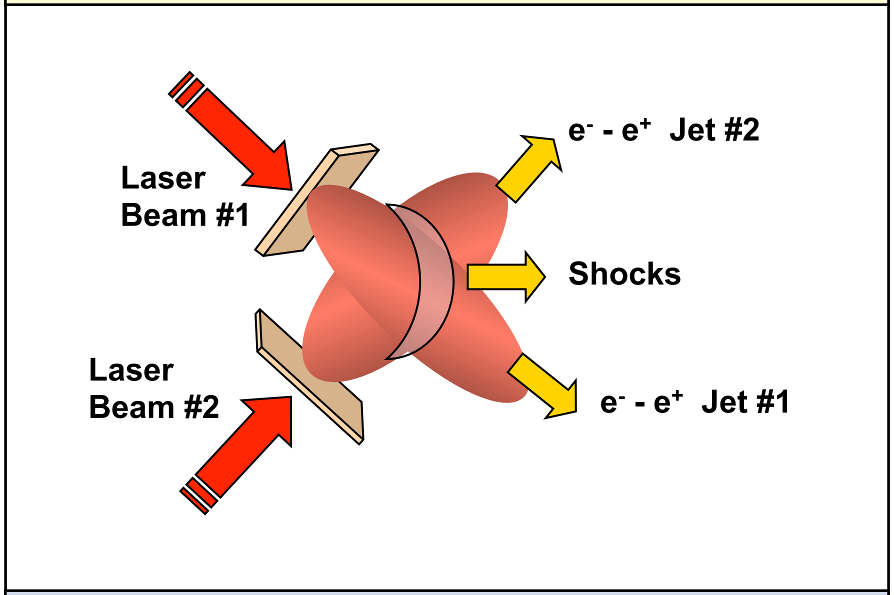
We will use laboratory pair jet interaction to understand astrophysical phenomena

Gamma-ray-burst (GRB) physics model



Internal shocks give off radiation/particles

Two-beam pair jet interaction experiment

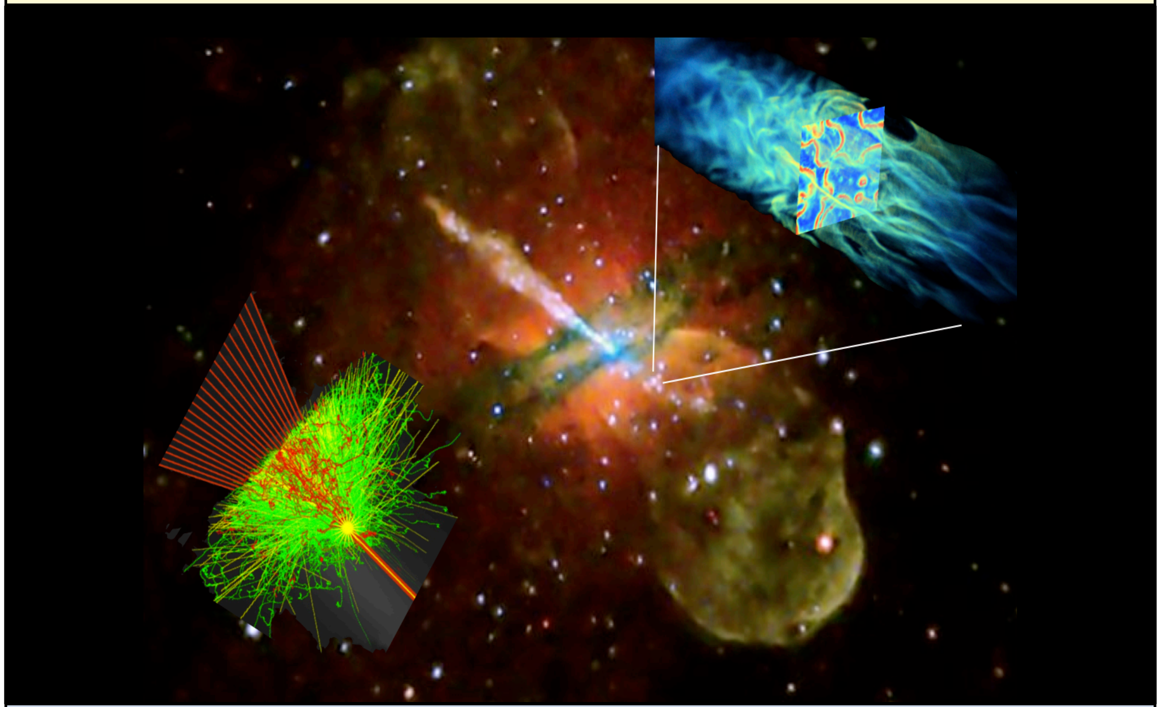


Relativistic e+-e- plasma jets interact

Colliding jets can mimic the internal shock of GRBs, allowing study of how energy is transferred to particles

Summary

Laser pair plasmas can simulate real events



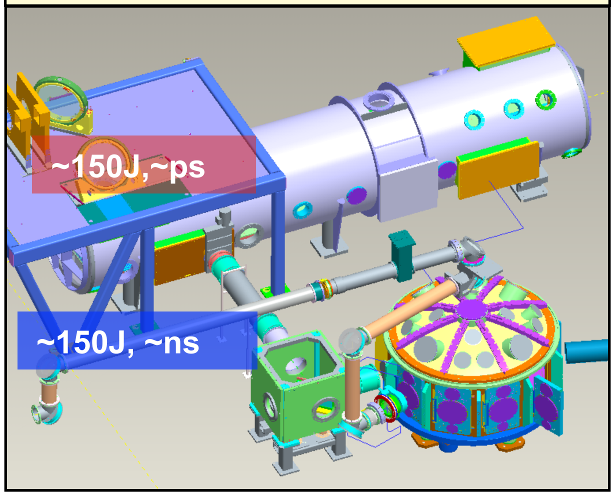
X-ray image of relativistically moving jets of electron-positron pair plasma powered by a supermassive black hole in a nearby galaxy Centaurus A. We may study this using the laser created relativistic pair jets to recreate relativistic collisionless shock waves that are thought to energize particles in astrophysical jets. (Chandra image credit: NASA/CXC/CfA/R.Kraft et al.

- **We have produced copious, relativistic positrons using high-energy, short-pulse lasers**
- **Many exciting applications can be found using this new source, among them the relativistic pair plasma creation**
- **Laser positron experiments will create and let us investigate astrophysically-relevant pair plasmas**

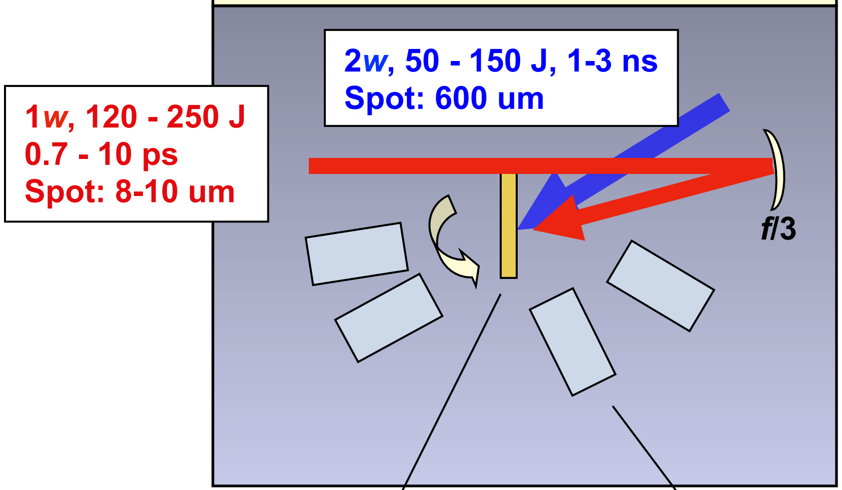

NIF

How: high energy *ps*-lasers laser is the key component in the experimental setup

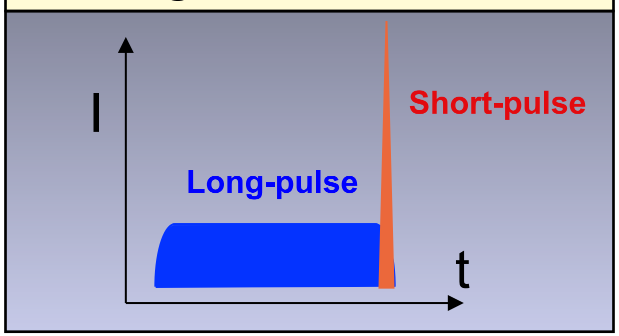
LLNL Titan two-beam laser



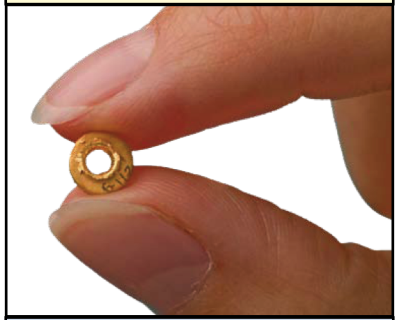
Experimental setup



Timing for the two beams

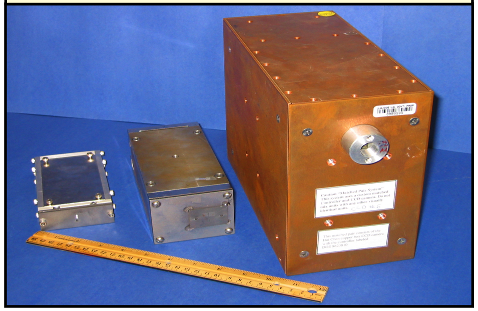


Targets



Al, Cu, Sn, Ta, Au
Thickness: 0.1 - 3.1 mm

Spectrometers



Chen et al. RSI 08